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Study of the first-excited $K^\pi = 0^+$ and 2^+ bands in ^{228}Th in the ^{226}Ra$(\alpha, 2n)$ reaction

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Abstract. Excited bands of ^{228}Th were studied in the ^{226}Ra$(\alpha, 2n)$ reaction by gamma-ray and conversion-electron spectroscopy. The first-excited $K^\pi = 0^+$ and 2^+ bands were identified up to $I^\pi = 12^+$ and 10^+, respectively. The spin dependence of the moments of inertia is discussed. The experimental data indicate a structural change of these bands from ^{228}Th to ^{230}Th and ^{232}Th.

PACS. 21.10.Re Collective levels and giant resonances – 23.20.Lv Gamma transitions and level energies – 27.90.+b $220 \leq A$

1 Introduction

The nuclear structure of heavy nuclei around $(N, Z) = (136, 88)$ (^{222}Rn, ^{224}Ra, ^{226}Th) has been interpreted successfully by assuming reflection-asymmetric (octupole deformed) shapes [1]. The first evidence for such shapes came from the observation of unusually low lying $K^\pi = 0^-$ bands in even-even nuclei with the $I^\pi = 1^-$ band heads around 250 keV [2]. These excitation energies are very low compared to the energies of ∼1 MeV for octupole-shape oscillations, but still ∼ 200 keV higher than the 1^- members of the alternating-parity ground bands predicted for nuclei with stable octupole deformation. However, the expected regular interspacing of the ground-state $K^\pi = 0^+$ and the first-excited $K^\pi = 0^-$ bands develops for spins above ∼6. This was taken as evidence for the formation of reflection-asymmetric shapes at higher spins.

The alternating-parity ground bands in even-even nuclei have so far provided the only evidence for the spin evolution of stable octupole deformation. Moreover, it has been pointed out that the observed octupole rigidity at high spins is rather difficult to understand in view of the theoretical prediction of only modest octupole barriers [1]. It is thus important to obtain additional information on this phenomenon - and on the effects of reflection-asymmetric deformations in even-even nuclei in general - from excited rotational bands. The investigation of bands up to high spins requires the measurement of γ-rays following compound reactions. Such measurements are difficult due to the lack of suitable targets and the overwhelming fission cross-sections leading to a large γ-ray background from the fission fragments. In a study of the light thorium isotopes in ^{226}Ra(α, xn) reactions [3] we observed in ^{228}Th a large number of high-energy γ-rays in the spectrum in coincidence with conversion electrons of the $4^+ \to 2^+$ ground-band transition. This encouraged a study of excited bands in the ^{226}Ra$(\alpha, 2n)^{228}$Th reaction with the moderately large $\gamma - \gamma$ coincidence setup available at our cyclotron, and the present work gives the results of this investigation, leading to the extension of the first-excited $K^\pi = 0^+$ and 2^+ rotational bands in ^{228}Th (denoted in the following for simplicity as β and γ bands, respectively) to intermediate spins.

2 Experimental methods and results

A target of $\sim 300\mu g/cm^2$ of ^{226}Ra was bombarded with 28 MeV α-particles from the Bonn cyclotron. Gamma rays in the resulting compound reaction were measured by three Compton-suppressed Ge detectors in coincidence with the L_{II} conversion-electrons of the $4^+ \to 2^+$ ground-band transition detected with an iron-free orange spectrometer. The γ-ray spectrum in the energy region from 400 to 1150 keV is shown in Fig. 1 (the low-energy part of this spectrum is shown in Fig. 5 of ref. [3] where also details on the experimental technique can be found). In the present context this spectrum provides two pieces of information: (i) All γ-rays assigned below to the β and γ bands proceed via the $4^+ \to 2^+$ member of the ground band. The γ-ray intensities derived from the coincidence spectrum of Fig. 1 can thus be used as singles intensities. (ii) The gate electrons are essentially free from contributions from the decay of fission fragments, in contrast to the gated spectra in the $\gamma - \gamma$ coincidences. This enables in many cases the identification of background $\gamma - \gamma$ coincidences from fission fragments.

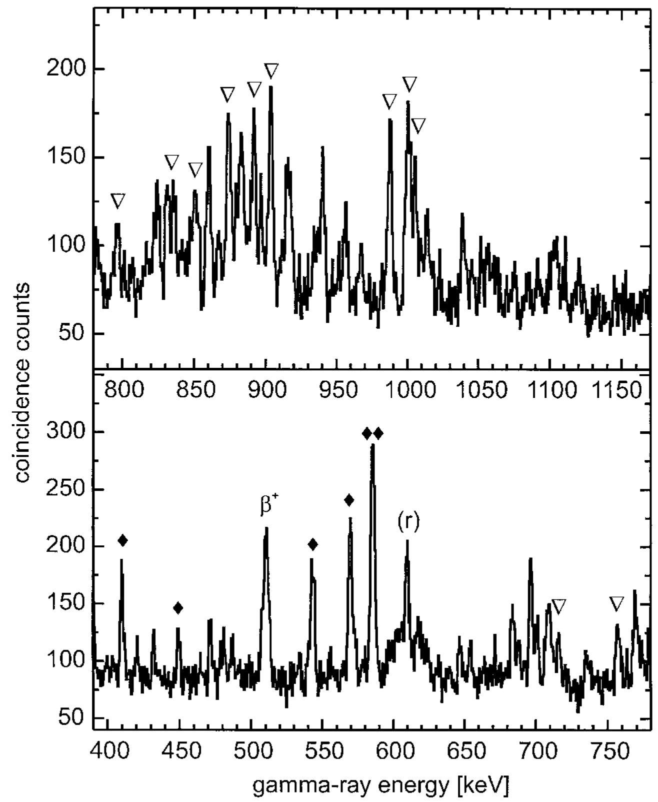

Fig. 1. Gamma-ray spectrum in coincidence with L_{II} conversion electrons of the $4^+ \to 2^+$ transition of the ground band of ^{228}Th. The γ-rays assigned as depopulating the β and γ bands are marked by *diamonds* and *triangles*, respectively

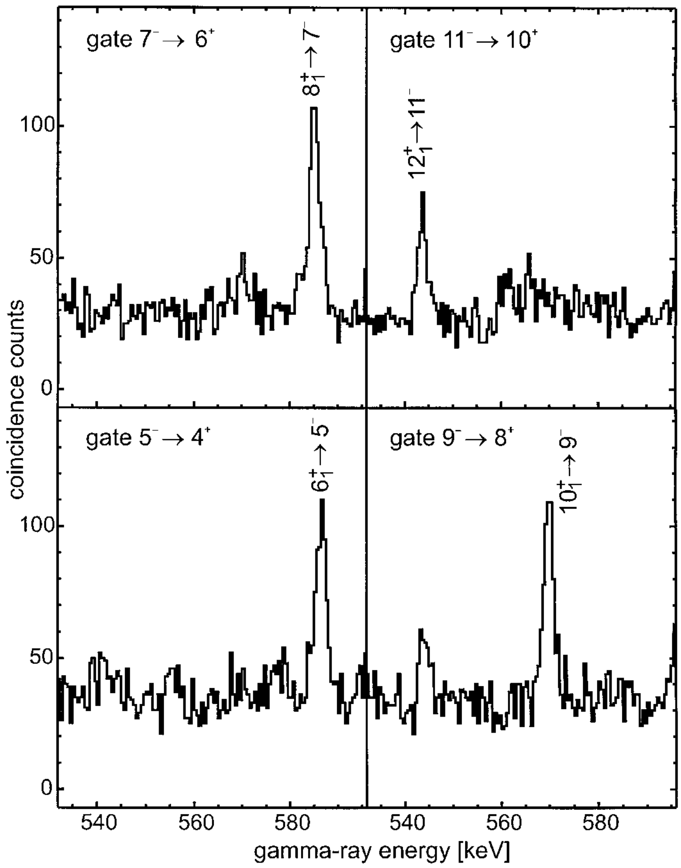

Fig. 2. Gamma-ray spectra in coincidence with successive $I^- \to (I-1)^+$ transitions from the first-excited $K^\pi = 0^-$ band to the ground band of ^{228}Th. The observed lines are interpreted as transitions from the first-excited $K^\pi = 0^+$ band as indicated by their markings

The technique of $e^- - \gamma$ coincidence measurements can only be used successfully for low-energy transitions with sufficiently high conversion coefficients, e.g. for E2 transitions with energies below ~200 keV. For an identification of excited rotational bands it is necessary to measure $\gamma - \gamma$ coincidences. We have performed such measurements in the ^{226}Ra$(\alpha, 2n)$ reaction with a $\gamma - \gamma$ coincidence setup consisting of four Compton-suppressed Ge detectors placed 17 cm from the target at 45°, 90° and ±135° to the beam direction. Some selected coincidence spectra are displayed in Figs. 2 and 3, showing the proposed transitions from the β band to the first-excited $K^\pi = 0^-$ band and from the γ band to the ground band, respectively.

The energies and relative intensities of the γ-rays assigned to the β and γ band are listed in Table 1. The total intensities of the transitions depopulating the β and γ band, observed in the $(\alpha, 2n)$ reaction, are shown in Fig. 4 together with those of the ground and first-excited 0^- bands (the reduced intensities of the even-spin members of the γ band presumably result from neglecting the contributions from the unobserved $I_\gamma \to (I \pm 2)_g$ transitions). With a total cross section for the ^{226}Ra$(\alpha, 2n)^{228}$Th reaction of ~1 b (estimated from the peak cross section of ~500 mb for the ^{226}Ra$(\alpha, 4n)^{226}$Th reaction [7]) one obtains cross sections for the excitation of the β and γ bands of ~20 mb.

3 Discussion

The levels of the first-excited $K^\pi = 0^+$ and 2^+ bands in ^{228}Th, and their dominant decays to the first-excited 0^- and ground band, are shown in Fig. 5. The low-spin members of the two bands were known from previous work up to the 4^+ and 6^+ levels, respectively [4,5,6].

The spin-dependence of the moments of inertia of the ground, β and γ bands is shown for the nuclei ^{228}Th, ^{230}Th and ^{232}Th in Fig. 6. This figure illustrates the structural change of these bands in the three nuclei: the β and γ bands in ^{230}Th and ^{232}Th have similar moments of inertia, ~ 10% and 20% larger, respectively, than those of the ground band. In ^{228}Th, in contrast, the moment of inertia of the γ band is only slightly larger than that of the ground band, whereas that of the β band is ~ 35% larger. The figure also shows, as observed earlier [12,13], that the nucleus-to-nucleus variation of the moment of inertia at low spins is much smaller for the β band than for the ground band. It furthermore indicates that the increase of the moment of inertia with increasing angular momentum in a given nucleus is similar for the ground and β band.

In Table 2 we have collected the moments of inertia of the ground band and the first two excited $K^\pi = 0^+$

Table 1. Energies and intensities of γ-rays from the first-excited $K^\pi = 0^+$ and 2^+ bands in ^{228}Th

Band $E_{b.h.}$ (keV)	K^π	Level[a] E_{exc} (keV)	I^π	Transition[a] $I\rightarrow$	I'	E_γ (keV)	$I_\gamma(exp)$	$I_\gamma(cal)$[b]
831.82	0^+	831.82 *1*	0^+	$0^+\rightarrow$	1^-	503.7 *2*	100 *5*	100
				$\rightarrow$	2^+	774.1 *2*	32 *5*	37.9
		874.47 2	2^+	$2^+\rightarrow$	3^-	478.45 *4*	109 *6*	101
				$\rightarrow$	1^-	546.45 *2*	100 *5*	100
				$\rightarrow$	4^+	687.8 *2*	17 *3*	21.1
				$\rightarrow$	2^+	816.5 *1*	13 *2*	27.8
				$\rightarrow$	0^+	874.5 *2*	26 *4*	27.3
		968.43 *3*	4^+	$4^+\rightarrow$	5^-	449.23 *3*	58 *8*	60.5
				$\rightarrow$	3^-	572.3 *1*	100 *11*	100
				$\rightarrow$	6^+	590.1 *3*	1.5 *5*	6.8
				$\rightarrow$	4^+	781.9 *2*	13 *3*	15.9
				$\rightarrow$	2^+	910.7 *1*	47 *8*	37.5
		1105.4 *2*	6^+	$6^+\rightarrow$	7^-	409.9 *2*	89 *11*	39.8
				$\rightarrow$	5^-	586.4 *2*	100 *44*	100
				$\rightarrow$	4^+	918.1 *3*	83 *11*	38.7
		1280.5 *2*	8^+	$8^+\rightarrow$	9^-	359.6 *2*	30 *10*	26.1
				$\rightarrow$	7^-	585.0 *2*	100 *30*	100
				$\rightarrow$	6^+	902.3	masked	36.5
		1490.4 *3*	10^+	$10^+\rightarrow$	11^-	300.6 *3*	33 *13*	16.2
				$\rightarrow$	9^-	569.5 *2*	100 *13*	100
				$\rightarrow$	8^+	867.1 *5*	14 *4*	33.1
		1733.2 *3*	12^+	$12^+\rightarrow$	13^-	236.0 *3*	25 *8*	8.9
				$\rightarrow$	11^-	543.3 *2*	100 *17*	100
				$\rightarrow$	10^+	821.6 *4*	15 *11*	29.2
968.97	2^+	968.97 *1*	2^+	$2^+\rightarrow$	4^+	782.1 *1*	1.4 *2*	2.3 (3.6)
				$\rightarrow$	2^+	911.20 *2*	100 *2*	100
				$\rightarrow$	0^+	968.98 *2*	62 *2*	95.2 (76.8)
		1022.53 *1*	3^+	$3^+\rightarrow$	4^+	835.65 *2*	33 *3*	19.5 (31.2)
				$\rightarrow$	2^+	964.80 *2*	100 *6*	100
		1091.02 *3*	4^+	$4^+\rightarrow$	6^+	713.1 *3*	1.8 *4*	2.6 (5.0)
				$\rightarrow$	4^+	904.19 *3*	100 *5*	100
				$\rightarrow$	2^+	1033.25 *9*	26.5 *9*	66.2 (38.4)
		1174.51 *10*	5^+	$5^+\rightarrow$	6^+	796.2 *1*	48 *10*	19.4 (40.8)
				$\rightarrow$	4^+	987.7 *1*	100 *12*	100
		1270.0 *2*	6^+	$6^+\rightarrow$	6^+	891.8 *2*	100 *8*	100
				$\rightarrow$	4^+	1083.2	weak	71.2 (27.9)
		1379.5 *3*	7^+	$7^+\rightarrow$	8^+	756.9 *3*	50 *19*	16.5 (46.0)
				$\rightarrow$	6^+	1001.3 *3*	100 *13*	100
		1497.3 *3*	8^+	$8^+\rightarrow$	8^+	874.7 *3*	100 *15*	100
				$\rightarrow$	6^+	1119.1	weak	82.1 (19.7)
		1627.9 *3*	9^+	$9^+\rightarrow$	10^+	715.9 *3*	38 *8*	13.3 (49.6)
				$\rightarrow$	8^+	1005.4 *3*	100 *15*	100
		1762.8 *3*	10^+	$10^+\rightarrow$	10^+	850.8 *3*	100 *50*	100
				$\rightarrow$	8^+	1140.2	weak	96.4 (12.1)

[a]) The results listed for $I^\pi \leq 5^+$ are from radioactive decay work [4,5,6]
[b]) Alaga values for B(E2) ratios and $R = 2.1 \cdot 10^{-3} fm^{-1}$ for $B(E1)/B(E2)$. Values in parenthesis: generalized intensity relation with $a_2 = 0.017$ (see text)

bands at low and high spins for even-even Ra, Th, U and Pu nuclei. It is remarkable that the values for the excited 0^+ bands in the thorium and uranium nuclei vary only by $\sim 5\%$ in a mass region of changing quadrupole deformation where the values for the ground band are changing by almost a factor of 2. It has to be noted, however, that the first-excited $K^\pi = 0^+$ bands in the actinides are known to have properties very different from those expected for β-vibrations (see e.g. [16]).

The most noticeable feature of the moments of inertia of the γ bands is the odd-even staggering: in ^{230}Th and ^{232}Th the even-spin members of the γ band are shifted to higher energies compared to the odd-spin members, whereas there is a small shift in the opposite direction

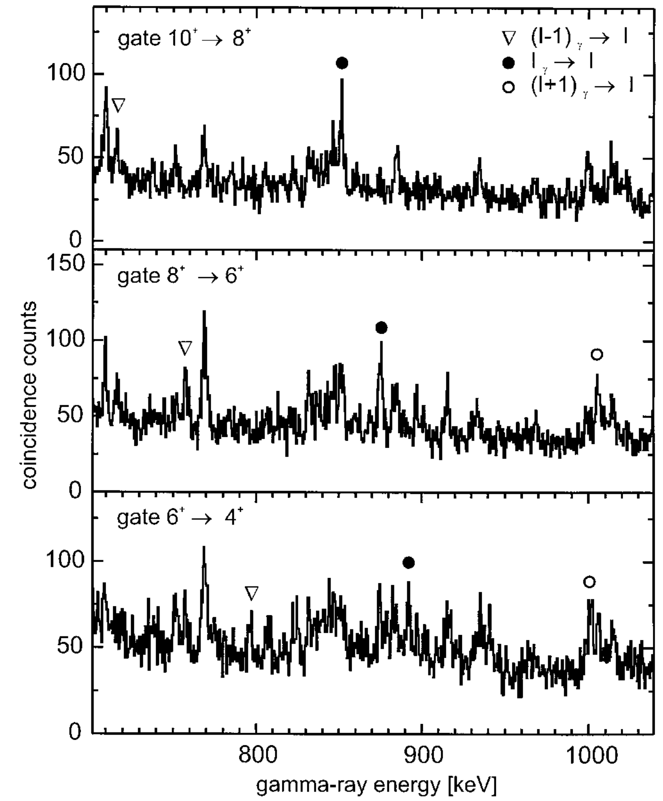

Fig. 3. Gamma-ray spectra in coincidence with successive transitions within the ground band of ^{228}Th. The lines interpreted as transitions from the γ band to the ground band are marked

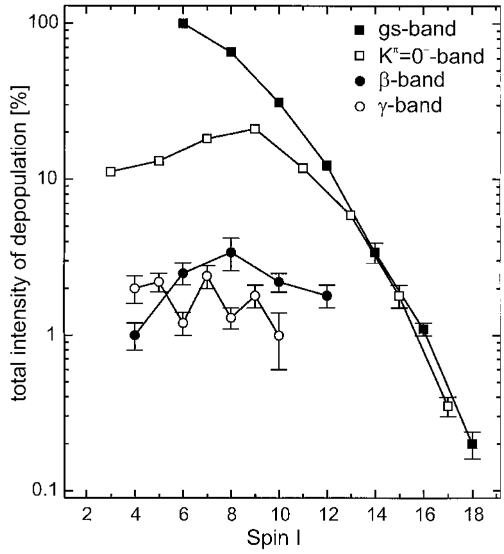

Fig. 4. Depopulation probability versus nuclear spin for the ground, first-excited 0^-, β and γ bands in ^{228}Th, as observed in the ^{226}Ra$(\alpha, 2n)^{228}$Th reaction

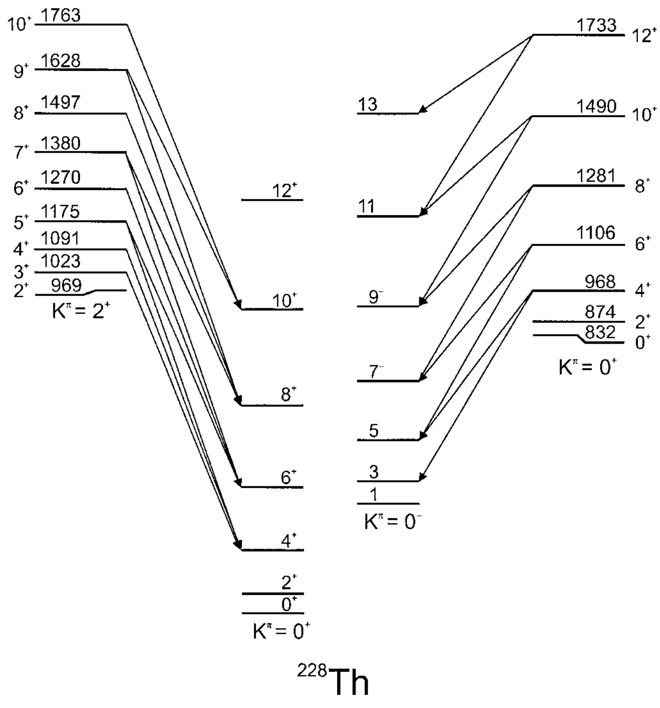

Fig. 5. Partial level scheme of ^{228}Th showing the first-excited $K^\pi = 0^+$ and 2^+ bands observed in the ^{226}Ra$(\alpha, 2n)^{228}$Th reaction

in ^{228}Th. These shifts are probably caused by couplings of the γ band with close-lying $K^\pi = 0^+$ bands. This is most obvious for ^{230}Th and ^{232}Th for which the magnitudes of the upward shifts strongly suggest a coupling of the γ bands to the lower-lying first-excited 0^+ bands: the observed energy gaps between the 2^+ members of the two bands is 104 keV for ^{230}Th and 11 keV for ^{232}Th.

In order to investigate the coupling of the β and γ bands in ^{230}Th and ^{232}Th more quantitatively we have performed two-band mixing calculations. The matrix elements of the $\beta-\gamma$-coupling were assumed to have the form $\langle\gamma|H_c|\beta\rangle = \sqrt{2(I-1)I(I+1)(I+2)} \cdot h_2$ [17], and h_2 was varied for every spin to obtain a smooth spin dependence of the moments of inertia for the unperturbed γ bands. The γ band in ^{232}Th requires a spin dependence of the interaction strength with $|h_2|$ decreasing from $\sim$0.2 keV for I = 2 to $\sim$ 0.1 keV for $I = 12$ ($|h_2(I)| \approx 0.207 + 0.0006(I-2) - 0.00126(I-2)^2$), whereas the γ band in ^{230}Th is described with $|h_2| = 0.15$ keV. The spin dependence of h_2 for ^{232}Th might result from an increasing coupling of the γ band to higher-lying $K^\pi = 0^+$ bands with increasing spin, and thus the low-spin result of $|h_2| \approx 0.21$ keV probably represents the true $\beta-\gamma$ coupling. The corresponding coupling in the deformed rare earth nuclei seems to be approximately twice as strong (see e.g. [18]). This is not surprising since the structure of the first-excited $K^\pi = 0^+$ bands in the rare earth and actinide regions is known to be quite different.

The cause of the odd-even staggering of the γ band in ^{228}Th is less clear. The downward shifts of the even-spin members indicate a stronger coupling to higher-lying $K^\pi = 0^+$ bands than to the first-excited one. We note in this connection the difference in the structure of the β and γ bands of ^{228}Th indicated by the differences in their

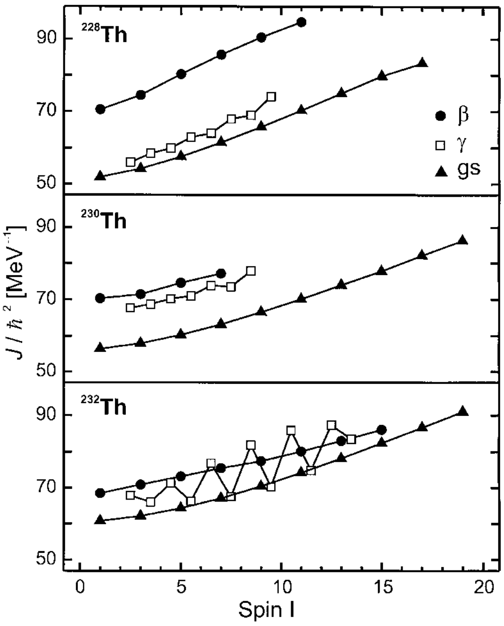

Fig. 6. Moments of inertia versus spin for the ground bands and the first-excited $K^\pi = 0^+$ and 2^+ bands (β and γ bands) of ^{228}Th, ^{230}Th [8] and ^{232}Th [9,10,11]

moments of inertia discussed above. A second-excited 0^+ band in ^{228}Th has also a large moment of inertia, but a third 0^+ band has been proposed with its 2^+ and 4^+ members 206 and 199 keV above the corresponding levels of the γ band, indicating similar moments of inertia of these latter two bands [5]. One possible explanation for the observed odd-even staggering in ^{228}Th might thus be that the γ band couples only very weakly to the first two excited 0^+ bands, but rather strongly to the third one.

The experimental γ-ray branching ratios for the transitions from the β and γ bands to the ground and first-excited $K^\pi = 0^-$ bands are compared in Table 1 with calculated values. All transitions between levels with equal or opposite parities are assumed to have pure E2 or E1 multipolarities, respectively. The values listed for the β band are calculated using the Alaga relations for the E1 and E2 branchings. For the E1 to E2 branchings a ratio of the transition matrix elements (see [17], (4-92)) of

$$R = \left| \frac{\langle 0^- | M(E1,0) | 0^+ \rangle}{\langle 0_g^+ | M(E2,0) | 0^+ \rangle} \right| = (2.1 \pm 0.2) \cdot 10^{-3} fm^{-1}$$

is derived from the experimental γ -ray branchings of the 0^+ level and the $[I^+ \to (I-1)^-]$ to $[I^+ \to (I-2)^+]$ branchings of the 2^+ and 4^+ levels of the β band. The agreement of the experimental and calculated branching ratios is reasonable bearing in mind that band mixings have been neglected (see [8] for a discussion of such mixing effects).

The Alaga values for the E2 branchings from the γ band to the ground band deviate appreciably from the experimental results. Here it is possible to take into account the coupling of the γ band with the ground band,

Table 2. Comparison of moments of inertia of the ground and excited 0^+ bands in even-even actinide nuclei

Nucleus	$E_{exc}(0^+)^a$ (keV)	$J/\hbar^2[MeV^{-1}]^b$ g	0^+	$J(0^+)/J(g)^c$ I	II
^{226}Ra	824.6	44.33 *1*	61.1 *2*	1.38	1.26
^{228}Ra	721.2	47.01 *2*	60.6 *1*	1.29	
^{226}Th	805.2	42.74 *2*	70.4 *9*	1.65	
^{228}Th	831.8	51.94 *1*	70.4 *1*	1.36	1.35
	938.6		73.2 *2*	1.41	
^{230}Th	634.9	56.39 *2*	70.3 *2*	1.25	1.22
^{232}Th	730.4	60.77 *1*	68.6 *4*	1.13	1.08
^{232}U	691.4	63.06 *1*	69.6 *1*	1.10	1.07
	927.3		74.5 *3*	1.18	
^{234}U	809.9	68.97 *1*	71.7 *2*	1.04	1.24
	1044.5		73.6 *3*	1.07	
^{236}U	919.2	66.31 *1*	73.0 *6*	1.10	
^{238}U	925.7	66.80 *5*	72.1 *7*	1.08	
	996.7		73.9 *12*	1.11	
^{238}Pu	941.5	68.06 *5*	72.1 *4*	1.06	
^{240}Pu	860.7	70.05 *1*	75.7 *2*	1.08	
	1089.4		72.3 *3*	1.03	

^{a}) Experimental data from Nuclear Data Sheets and refs. [8,14,15]
^{b}) Calculated from the $2^+ \to 0^+$ transitions of the ground band (g) and excited 0^+ bands (0^+)
^{c}) I: $2^+ \to 0^+$ transitions; II: $12^+ \to 10^+$ transitions for ^{228}Th and ^{232}Th, $10^+ \to 8^+$ transition for ^{232}U and $8^+ \to 6^+$ transitions for ^{226}Ra, ^{230}Th and ^{234}U

which is expected to have a dominating effect on the E2 branchings, neglecting again the coupling of the γ band to excited $K^\pi = 0^+$ bands: the odd-spin members of the γ band are not influenced by these excited bands, and the E2 branchings should therefore follow the generalized intensity relation (see [17], (4-230))

$$\frac{B(E2, I_\gamma \to (I+1)_g)}{B(E2, I_\gamma \to (I-1)_g)} = \frac{I-1}{I+2} \left(\frac{1 + 2 \cdot (I+1) \cdot a_2}{1 - 2 \cdot I \cdot a_2} \right)^2$$

From the experimental branching ratios of the odd-spin members an average value of $a_2 = -M_2/M_1 = 0.017(4)$ is derived (for a definition of the M_i see [17]). The branching ratios calculated using this value in the generalized intensity relation are listed in the last column of Table 1 (values in parenthesis). The comparison with the experimental values demonstrates that the mutual ground - γ coupling is indeed responsible for most of the deviations of the branching ratios from the Alaga values.

4 Conclusion

We have identified the β and γ bands in ^{228}Th to intermediate spins in the $(\alpha, 2n)$ compound reaction. To our knowledge only one comparable report exists for nuclei in the region of strong octupole correlations around $A = 225$, our study of ^{226}Ra in the (d, pn) deuteron-breakup reaction, where the β band was identified up to the 8^+ level

[13]. Both these isotones are located in the transition region from stable octupole to pure quadrupole deformation. The alternating-parity ground band expected for stable octupole deformation is reached at $I \approx 10$ and ≈ 15 in ^{226}Ra and ^{228}Th, respectively. In both nuclei the moment of inertia of the β band is $\sim 35\%$ larger than that of the ground band independent of spin, with a slight indication of a possible saturation at the highest spins observed (see Fig. 6 and Fig. 5 of [13]). Unfortunately, the highest spins observed in the present work on ^{228}Th and the previous work on ^{226}Ra are still 2 to 4 units below the critical spins.

In addition to the γ-rays assigned in the present work as deexciting the β and γ bands we observe a number of as yet unassigned γ-rays of comparable intensities. Since our measurements were made with a small detector array it is very probable that the β and γ bands could be extended to higher spins, and additional bands could be identified in measurements with the large existing detector arrays. Such measurements, and an extension to the ^{226}Ra$(\alpha, 4n)^{226}$Th reaction, would be very interesting.

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References

1. Butler, P.A., Nazarewicz, W.: Rev. Mod. Phys. **68**, 349 (1996)
2. Stephens, F.S., Asaro, F., Perlman, I.: Phys. Rev. **100**, 1543 (1955)
3. Ackermann, B., Baltzer, H., Ensel, C., Freitag, K., Grafen, V., Günther, C., Herzog, P., Manns, J., Marten-Tölle, M., Müller, U., Prinz, J., Romanski, I., Tölle, R., deBoer, J., Gollwitzer, N., Maier, H.J.: Nucl. Phys. **A559**, 61 (1993)
4. Artna-Cohen, A.: Nuclear Data Sheets **80**, 723 (1997)
5. Weber, T., deBoer, J., Freitag, K., Gröger, J., Günther, C., Manns, J., Müller, U.: Z. Phys **A358**, 281 (1997)
6. Weber, T.: PhD thesis, University of Bonn (1997)
7. Vandenbosch, R., Seaborg, G.T.: Phys. Rev. **110**, 507 (1958)
8. Ackermann, B., Baltzer, H., Freitag, K., Günther, C., Herzog, P., Manns, J., Müller, U., Paulsen, R., Sevenich, P., Weber, T., Will, B., de Boer, J., Graw, G., Levon, A.I., Loewe, M., Lösch, A., Müller-Zanotti, E.: Z. Phys. **A350**, 13 (1994)
9. Schmorak, M.R.: Nuclear Data Sheets **63**, 139 (1991)
10. Ackermann, B.: PhD thesis, University of Bonn (1992)
11. Kröll, T.: PhD thesis, University of Frankfurt (1996)
12. Venema, W.Z., Jansen, J.F.W., Janssens, R.V.F., van Klinken, J.: Phys. Lett. **156B**, 163 (1985)
13. Ackermann, B., Fleischmann, Ch., Baltzer, H., de Boer, J., Czosnyka, T., Günther, C., Müller, U., Weber, T.: Z. Phys. **A355**, 151 (1996)
14. Ardisson, G., Hussonnois, M., LeDu, J.F., Trubert, D., Lederer, C.M.: Phys. Rev. **C49**, 2963 (1994)
15. Hoogduin, J.M., Ditzel, E., Balanda, A., de Boer, F.W.N., Bokemeyer, H., Gerl, J., Heyde, K, van Klinken, J., Krasznahorkay, A., Salabura, P., Wollersheim, H.J.: Phys. Lett. **B384**, 43 (1996)
16. Sood, P.C., Headly, D.M., Sheline, R.K.: Atomic Data and Nuclear Data Tables **51**, 273 (1992)
17. Bohr, A., Mottelson, B.R.: Nuclear structure, Vol. II. Reading, Mass.: Benjamin (1975)
18. Günther, C., Boehmsdorff, S., Freitag, K., Manns, J., Müller, U.: Phys. Rev. **C54**, 679 (1996)